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METHOD AND APPARATUS FOR PATH SELECTION
AND WAVELENGTH ASSIGNMENT IN AN OPTICAL NETWORK

BACKGROUND

There exist numerous algorithms for the standard routing problem, in which a
5 network is modeled as a directed graph, and it is assumed that traffic from one link can
always be relayed to its consecutive link. Among these algorithms, the most efficient
one is the well-known Dijkstra algorithm, which has been adopted for use in many of
the common link-state routing protocols, such as Open Shortest Path First (OSPF),
Intermediate System to Intermediate System (IS-IS), and Private Network to Network
10 Interface (PNNI).

An important class of routing problem pertains to dynamically searching for an
optimal lightpath between two edge nodes of an optical network. The path consists of
one or more optical links, each link having a dedicated wavelength for the path. The
wavelength, or optical channel, assigned to the path may not be the same on every link.
15 Every time the wavelength assignment changes along the path, special wavelength
conversion equipment, e.g., an optical-electrical-optical (OEO) conversion device, is
required.

In optical network routing, both routing and wavelength assignment have to be
considered simultaneously. In addition, since there may not be a full OEO conversion
20 capability at every node, traffic arriving at a node on one wavelength of a link may not
be able to be relayed to another wavelength of a consecutive link of the lightpath.
Therefore, the standard graph model cannot be used directly.

In "Lightpath (Wavelength) Routing in Large WDM Networks", Chlamtac et. al., IEEE Journal on Selected Areas in Communications, Vol. 14, No. 5, June 1996, it is proposed to convert the original graph to a new, matrix-like structure with m rows and N columns (N and m being the number of network nodes and wavelengths respectively), with each column corresponding to a node and each row corresponding to a wavelength. Links in the horizontal direction represent connectivity between neighboring nodes, using the available wavelengths on the optical fibers that interconnect the physical nodes. Links in the vertical direction represent connectivity between different wavelengths within a single physical node that are made available by OEO transmitters and receivers. The resulting graph is called a "wavelength graph." Chlamtac et al. further derive a routing and wavelength assignment algorithm, referred to as the Shortest Path Algorithm for the Wavelength Graph (SPA WG), with computation complexity of $O\{(N+m)Nm\}$. However, the SPA WG algorithm is understood to contain an error and therefore is not practically available. Moreover, the SPA WG algorithm is not Dijkstra-based and thus is difficult to integrate with standard routing protocols such as OSPF.

SUMMARY

A method used to find the optimal path in an optical network should ensure that sufficient OEO transmitters and receivers, if necessary, are available along the path. In addition, the method needs to find the lowest cost path, where the cost typically reflects the usage of equipment and facilities along the path. The method should also be simple enough to execute in real time, as the paths need to be calculated in real time as users generate connection requests.

The present approach enables an optical switch to dynamically find an optimal path, with a wavelength or optical channel and OEO equipment (if necessary) dedicated to the path on each link. Using a wavelength graph to represent the optical network, the approach represents as an electronic node the electronic switching fabric that interconnects OEO equipment within a physical node. The transformation of the

network representation to include the electronic node greatly reduces the number of links in the wavelength graph and significantly increases the computational efficiency.

Accordingly, a method of determining a shortest path between a source node and a destination node in an optical network that has plural network nodes interconnected with optical transmission links includes representing the network as a uni-directional graph $G = \langle V, E \rangle$ with V defining a set of network nodes and E defining a set of uni-directional optical transmission links. The graph G is transformed to a wavelength graph $G' = \langle V', E' \rangle$ with V' defining a set of electronic nodes and optical channel nodes corresponding to the network nodes in set V and with E' defining a set of internal links and optical channel links. The optical channel links correspond to the optical transmission links in set E . A single-source shortest path algorithm (e.g., Dijkstra's algorithm) is applied to the graph G' to determine a shortest path corresponding to an optimal path on graph G .

The transforming features assigning an electronic node to each network node that represents an electronic switching fabric interconnecting optical-electrical-optical (OEO) transmitters and receivers of the network node. Optical channel nodes are assigned to each network node that represent an optical cross-connect for an optical channel available at the network node. For each network node, an internal link is assigned from the electronic node to each optical channel node if an associated OEO transmitter is available for the corresponding optical channel and an internal link is assigned to the electronic node from each optical channel node if an associated OEO receiver is available for the corresponding optical channel. For each optical transmission link, an optical channel link is assigned between a pair of optical channel nodes of corresponding network nodes if the corresponding optical channel is available on the associated optical transmission link.

Costs are assigned to the internal links in relation to OEO conversion costs. Costs are assigned to the optical channel links in relation to costs of the corresponding optical transmission links.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.

FIG. 1 illustrates an optical network of nodes interconnected with optical transmission links.

10 FIG. 2 is a block diagram of a network node in the network of FIG. 1.

FIG. 3 illustrates a pair of connected nodes.

FIG. 4 illustrates a transformation of one of the nodes in FIG. 3 according to the present approach.

15 FIG. 5 illustrates a transformation of another of the nodes in FIG. 3 according to the present approach.

FIG. 6 illustrates interconnection of the transformed nodes of FIGs. 4 and 5.

FIG. 7A illustrates a first lightpath that connects through the nodes of FIG. 3.

FIG. 7B illustrates the lightpath of FIG. 7A transformed according to the present approach.

20 FIG. 8A illustrates a second lightpath that connects through the nodes of FIG. 3.

FIG. 8B illustrates the lightpath of FIG. 8A transformed according to the present approach.

FIG. 9 is a flow diagram illustrating a method of the present approach.

DETAILED DESCRIPTION

25 FIG. 1 illustrates an exemplary optical network. The network includes network nodes 10-A, 10-B, 10-C, 10-D interconnected with optical transmission links 20. A lightpath interconnects edge nodes 12, 14 through network nodes A, C and D over links 20 and edge links 22. The lightpath includes optical channels 24A, 24B, 24C, 24D

carried on the respective links. In particular, optical channels 24A and 24B occupy wavelength λ_1 and do not require any OEO conversion at node A. At node C, OEO equipment 100 converts wavelength λ_1 of optical channel 24B to wavelength λ_2 of optical channel 24C. Optical channels 24C and 24D occupy wavelength λ_2 and do not
 5 require any OEO conversion at node D.

FIG. 2 shows a network node 10 for use in the optical network of FIG. 1. The network node includes OEO transmitters/receivers 100, an electronic switching fabric 110, a processor 120 and memory 130. The switching fabric 110 provides interconnection of the OEO transmitters and receivers under control of the processor
 10 120. In an embodiment, the memory 130 includes program code for determining an optimal path through the network, as described herein.

The network node 10 further includes an optical cross-connect (OXC) 106 which connect to ports 102-1, 102-2,...,102-N. Each port connects to an incoming or outgoing transmission link. The OXC 106 includes OXC planes 104-1, 104-2,...,104-M. Each of
 15 the OXC planes is used to switch or connect data signals from an incoming transmission link to an outgoing transmission link using one wavelength. For a path that uses, e.g., wavelength λ_1 on two consecutive links e and f, traffic is switched from one port (connecting to link e) to another port (connecting to link f) using an OXC-plane λ_1 . If a path uses two different wavelengths, e.g., λ_1 and λ_2 , on two consecutive links g and h,
 20 then traffic arriving from link g passes through OXC-plane λ_1 to the OEO equipment 100, through the switching fabric 110 and back to the OEO equipment, then to OXC-plane λ_2 , and leaves the node on link h. Thus, an optical channel node in a network node represents an OXC-plane for the corresponding optical channel.

The present approach uses a wavelength graph to represent a network of nodes.
 25 In addition, an "electronic node" is defined to represent the electronic switching fabric that physically interconnects OEO receivers with OEO transmitters within a physical node. As a result, the number of links in the wavelength graph is greatly reduced, and the computational efficiency is significantly increased. A method of the present approach is now described.

An optical network, such as the network shown in FIG. 1, can be modeled as a uni-directional graph $G = \langle V, E \rangle$ with V and E representing the set of network nodes and uni-directional links, respectively. The total number of wavelengths available to each network node is given as m . The present approach, as described in the following pseudocode, derives a wavelength graph $G' = \langle V', E' \rangle$ and finds an optimal path through G' :

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step 1: for any  $v \in V$ 
    define an electronic node  $v_0 \in V'$  ;
    for  $i := 1 \dots m$ 
10      define an optical channel node  $v_i \in V'$  ;
        if an OEO transmitter is available for optical channel  $\lambda_i$ 
            define a link  $(v_0, v_i) \in E'$  with a cost of  $y/2$  ;
        if an OEO receiver is available for optical channel  $\lambda_i$ 
            define a link  $(v_i, v_0) \in E'$  with a cost of  $y/2$  ;

15  step 2: for any  $f \in E$ , assume  $f = (v, w)$  with a cost of  $x$  and  $v, w \in V$ 
        for  $i := 1 \dots m$ 
            if optical channel  $\lambda_i$  is available on  $f$ 
                define a link  $(v_i, w_i) \in E'$  with a cost of  $x$  ;

step 3: apply Dijkstra's algorithm on  $G'$  to search for a shortest path, which corresponds
20  to an optimal path on  $G$ .

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In the present approach, m optical channel nodes v_i ($i = 1, 2, \dots, m$) and an electronic node v_0 are defined for any node v in V . Optical channel node v_i represents OXC plane λ_i of node v . Electronic node v_0 represents the electronic switching fabric in node v . An internal link is defined from v_i to v_0 if and only if there is an available OEO

receiver for optical channel λ_i . Likewise, an internal link is defined from v_0 to v_i if and only if there is an available OEO transmitter for optical channel λ_i .

If there is an optical transmission link $f \in E$ connecting from network node v to network node w , then for any wavelength available on link f , say, λ_i ($i = 1, 2, \dots, m$), an optical channel link is defined from optical channel node v_i to w_i . The cost of each optical channel link is defined as the corresponding physical link cost.

In this way a new graph G' is obtained, with costs of both physical links and OEO conversion on graph G converted to costs of only links (i.e., internal and optical channel) on graph G' . Therefore, any path consisting of physical nodes with a wavelength assigned to each link is converted to a lightpath consisting of optical channel nodes and possibly electronic nodes.

Having transformed the graph G to a wavelength graph G' , the standard Dijkstra algorithm can be run on graph G' to search for a shortest path, which corresponds to an optimal path on the original graph G . It should be understood that other single-source shortest path algorithms, e.g., Bellman-Ford, can be applied to search for a shortest path on graph G' .

The foregoing approach to transformation of the wavelength graph is now described with an example. FIG. 3 illustrates an example of two nodes $R, S \in V$ with $m = 4$ that are connected by unidirectional physical link k having link cost x . In this case, only optical channels λ_1 and λ_4 are available on the link k .

FIG. 4 illustrates the transformation in graph G' of node R wherein all OEO transmitters and receivers are available. The node R is represented as optical channel nodes R_1, R_2, R_3, R_4 and electronic node R_0 . The full interconnection between the optical channel nodes and the electronic node within node R is indicated by internal links 20A each having link cost $y/2$.

FIG. 5 illustrates the transformation in graph G' of node S wherein OEO transmitters and receivers are only partially available. In particular, only OEO transmitters for optical channels λ_2 and λ_3 are available, and only OEO receivers for optical channels λ_1 and λ_3 are available in node S . Note that there is no OEO equipment

available for optical channel λ_4 . Rather, OXC-plane λ_4 is used to switch traffic from incoming transmission links to outgoing transmission links without wavelength conversion.

The node S is represented as optical channel nodes S_1, S_2, S_3, S_4 and electronic node S_0 . Interconnection between the optical channel nodes and the electronic node within node S is indicated by internal links 20B each having link cost $y/2$. The internal link cost $y/2$ can vary link by link within a node and can vary from node to node. However, in most cases, the same OEO equipments are used in the same node and therefore, costs associated with them are the same. It is more likely to have such costs vary from node to node.

Since there is no OEO equipment available for optical channel λ_4 , there are no corresponding internal links between optical channel node S_4 and electronic node S_0 .

FIG. 6 illustrates the interconnection of network nodes R and S as represented in the transformed wavelength graph G' . In particular, optical channel links 20C are indicated between optical channel nodes R_1 and S_1 and between optical channel nodes R_4 and S_4 , respectively, each having link cost x . The optical channel link cost x can vary link by link between the same nodes and for different transmission links.

The interconnection between optical channel nodes shown in FIG. 6 is consistent with the configuration of FIG. 3 wherein only wavelengths λ_1 and λ_4 are available on optical transmission link k .

FIG. 7A shows a lightpath that connects from a source node to a destination node through a network that includes the physical nodes R and S of FIG. 3. In particular, an optical channel received at node R on wavelength λ_3 is converted to wavelength λ_1 for connection to node S. At node S, wavelength λ_1 is converted to wavelength λ_2 .

FIG. 7B illustrates the lightpath of FIG. 7A transformed to the wavelength graph G' according to the present approach with wavelength conversions indicated at network nodes R and S. In particular, the wavelength conversion from λ_3 to λ_1 is indicated as successive links from optical channel node R_3 to electronic node R_0 and from node R_0 to

optical channel node R_1 . Likewise, the wavelength conversion from λ_1 to λ_2 is indicated as successive links from optical channel node S_1 to electronic node S_0 and from node S_0 to optical channel node S_2 .

FIG. 8A shows a second lightpath that connects from a source node to a
 5 destination node through a network that includes the physical nodes R and S of FIG. 3. In particular, an optical channel received at node R on wavelength λ_4 passes to node S without experiencing wavelength conversion at either node. FIG. 8B illustrates the lightpath of FIG. 8A transformed to the wavelength graph G' according to the present approach. In particular, since there is no wavelength conversion at the nodes R and S,
 10 the links are simply shown as connecting from optical channel node R_4 to optical channel node S_4 .

FIG. 9 is a flow diagram illustrating the method of the present approach that can be a process performed in one or more network nodes or by a separate network management computer. At 200, information relating to the topology of the network
 15 including links and costs is initialized or retrieved from a data base. At 202, the network topology is represented as a graph $G = \langle V, E \rangle$. The graph G is transformed to a wavelength graph $G' = \langle V', E' \rangle$ as defined above at 204. At 206, an optimal path is determined by applying the Dijkstra algorithm to the wavelength graph G' .

The computation complexity of the present approach is $O\{(mL) \times \log_2(mN)\}$,
 20 where m is the number of wavelengths, L is the number of links, and N is the number of nodes. In this manner, the present approach corrects and improves the SPAWG method so that a lightpath can be found efficiently and optimally. Since the present approach is Dijkstra-based, it can be integrated easily with standard link-state routing protocols such as OSPF.

25 The present approach can be used in any optical network with or without OEO conversions, including the two extreme cases in which an optical network either does not have OEO capability at all or has full OEO capability. On the other hand, an optical network with partial OEO capability combines the advantages of the two extreme

networks, and achieves cost effectiveness and low blocking probability at the same time. It is for this type of network that the proposed algorithm is particularly suited.

The approach for determining the optimal path through an optical network can be used for both connectionless and connection-oriented networks. In a connection-oriented network, routing decisions need to be made at connection setup. The present approach can be used to pre-compute paths from any source to any destination. The pre-computed paths can be stored in memory or a data base for access upon each connection request. However, after the next connection request that uses a pre-computed path, the optical channel and OEO availability information may have changed and thus the pre-computed paths may no longer be usable. The paths typically need to be recalculated after each successful connection establishment.

In a connection-oriented environment, routing decisions are made at a lower frequency, compared to a connectionless network in which a routing/forwarding decision typically needs to be made for every packet.

In a preferred embodiment, a path calculation is made whenever there is a new connection request, as the frequency of new connection requests is typically very low.

In any case, an update of network topology including changes to link costs and OEO / optical channel availability information is needed regularly. These update functions can be provided either in a centralized manner using a separate management station that physically connects to every network node, or in a distributed manner by each of the network nodes using standard routing protocols such as OSPF or IS-IS.

It will be apparent to those of ordinary skill in the art that methods disclosed herein may be embodied in a computer program product that includes a computer usable medium. For example, such a computer usable medium can include a readable memory device, such as a hard drive device, a CD-ROM, a DVD-ROM, or a computer diskette, having computer readable program code segments stored thereon. The computer readable medium can also include a communications or transmission medium, such as a bus or a communications link, either optical, wired, or wireless, having program code segments carried thereon as digital or analog data signals.

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims.

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